PPG Mil-Tough® Façade Panels: Research to Design
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ABSTRACT
Protection Engineering Consultants (PEC) has supported PPG Industries, Inc. (PPG) in the development of Mil-Tough® Light Weight Protective Panels for commercial façade and military protective application since 2008. Mil-Tough® panels are composed of (at most) three main components: an unreinforced strike-face (for ballistic resistance), inorganic ceramic binder (ICB) with reinforcement consisting of fiberglass fabric (for blast resistance), and MilTough™ polymer (to reduce debris into the occupied space). During 2009, an early version of the façade panels was installed in a building overseas. As a result of the installation, additional research was performed to improve the panel fabrication and design process for future projects.

The latest phase of the research and development in 2012 focused on developing a predictive engineering performance tool (flexural resistance function for use in a single-degree-of-freedom (SDOF) analysis) to facilitate the specification and design of the latest generation of Mil-Tough® panels for blast and fragmentation applications. This phase of the research program was accompanied by constituent material testing and characterization as well as, multi-scale static flexure testing and full-scale dynamic arena blast testing for validation of the design tool and determination of appropriate response limits for design. Concurrently, PPG updated the panel fabrication and production process resulting in a more robust and efficient assembly line producing a more consistent and higher quality panel. Most recently, the predictive engineering performance tool has been used to develop in-house “quick-design” tables for use by product specifiers and has also been used to develop designs for various proposals.

This material is based upon work for PPG supported by the Air Force Research Laboratory under Contract No. FA4819-11-C-0007. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Air Force Research Laboratory.
INTRODUCTION

Development of Mil-Tough® panels started internally at PPG Industries, Inc. prior to 2008. Protection Engineering Consultants (PEC) was added to the research team in 2008 to assist in evaluating the material for anti-terrorism and force protection (ATFP) applications. Initially PEC was tasked with evaluating a preliminary version of the panel subjected to blast loads. The shock tube testing was successful and led to additional research and development of the panels for use in the ATFP market. During 2009, an early version of the façade panels was installed in a building overseas. That installation led to the development of the next generation panel and to further research on improving the fabrication and design process. The main goals of the most recent test program in 2012 were to evaluate the blast performance of the latest generation Mil-Tough® panels (optimized for performance and produced on the updated production line), develop a predictive engineering performance tool, and validate the tool with full-scale static and dynamic testing. The validated design tool is a critical component that enables engineers to design and specify Mil-Tough® panels for blast and fragmentation applications in the commercial market.

PANEL EVOLUTION

Mil-Tough® Light Weight Protective Panels are composed of (at most) three main components: an unreinforced strike-face (for ballistic resistance), inorganic ceramic binder (ICB) with reinforcement consisting of fiberglass fabric (for blast resistance), and MilTough™ polymer (to reduce debris into the occupied space). A schematic of the general panel construction is shown in Figure 1. Mil-Tough® panels are produced in two forms: blast panels and ballistic panels. Blast panels are composed of ICB with evenly spaced layers of fiberglass fabric reinforcement. Ballistic panels are made up of a blast panel (at least half of the total panel thickness) with an additional fragment defeating strike-face cast integrally on the exterior (threat side).

Figure 1. General Cross-Section of Mil-Tough® Panel
During the past five years, several static and dynamic test programs were completed on early versions of the Mil-Tough® panel, including shock tube testing on 1.5-in (38.1 mm) blast panels in 2008, improvised explosive device (IED) testing of blast and ballistic panels in a spaced gap configuration in 2009, static flexural beam testing in 2010, and numerous rounds of ballistic testing. Concurrently, PPG was working to improve the panel constructability. Changes to the panel construction included new strike face formulation, incorporation of a different type of fiberglass reinforcement, simplification and optimization of fiberglass placement through the panel thickness, and incorporation of various aggregate types and sizes to improve ballistic performance. In 2011 the construction process was upgraded to an assembly line process, which replaced the previous “one-off” approach, greatly improving the consistency of the end product. In 2012 material tests, static flexural tests, and a full-scale blast test were performed on the next generation panel to support development of a fast-running design tool.

**TEST RESULTS FOR MODEL VALIDATION**

Static and dynamic testing was performed to better understand panel performance and validate the flexural model. PEC observed material testing and static flexural testing (beam and full panel load-tree), then analyzed and incorporated results into a preliminary response model. One large-scale blast test on sixteen Mil-Tough® panels was also performed to evaluate the performance of Mil-Tough® panels subjected to blast loads. All static and dynamic test data was used to calibrate the Mil-Tough® panel model and to determine appropriate response limits for design.

**Material Testing.** Material testing was performed by PPG to characterize the behavior of the constituent materials (ICB and fiberglass) to obtain a fundamental understanding of the behavior of the composite Mil-Tough® panel system. Tensile, compression, and shear testing on the constituent materials was performed to determine general material properties. The interaction and bond between the ICB and fiberglass reinforcing was also evaluated. The material properties and engineering mechanics were used to develop a preliminary flexural strength predictive model. Static beam bending tests (with an 8-in (203 mm) span) were also performed to optimize the reinforcement arrangement in the Mil-Tough® panel cross-section.

**Static Testing.** Several series of static flexure tests were performed, including 6-ft (1.8 m) span beam bending tests at PPG and 10-ft (3.1 m) span panel load-tree tests at Air Force Research Lab (AFRL) test facilities located at Tyndall Air Force Base in Panama City, Florida, to better define the behavior of Mil-Tough® panels under flexural loading. The static data was used to refine and calibrate the flexural model for Mil-Tough® panels. In addition, the static load-tree test data, which pushed full-scale panels to failure (see Figure 2), was used to help determine response limits for design. A 1.5-in (38.1 mm) blast panel deflected around 20-in (508 mm) over a 10-ft (3.1 m) span, as shown in Figure 3, which is equivalent to a support rotation of about 13 degrees. Three important observations were drawn from the static load-tree tests: (1) panels failed by formation of flexural hinges and had little to no capacity beyond the first peak, (2) an inverse relationship exists between the support rotation at failure
and the panel thickness, and (3) a direct relationship exists between the maximum load on the panels and panel thickness.

![Figure 2. Static Load Tree Test Results: 1.5-in (38.1 mm) Blast Panel](image)

**Blast Testing.** Dynamic testing was performed to determine dynamic failure mechanisms and validate the final Mil-Tough® panel flexural response model. PEC assisted in planning one full-scale blast test on 16 Mil-Tough® panels at the AFRL. Panels tested ranged from 1.5-in (38.1 mm) to 3-in (76.2 mm) thick with a 2.5-ft (0.76 m), 4-ft (1.2 m), 10-ft (3.1 m), and 11-ft (3.4 m) spans. All Mil-Tough® blast and ballistic panels responded essentially “elastically” with very fine to hairline cracking noted on the interior face as shown in Figure 4. The 1.5-in (38.1 mm) blast panel with 11-ft (3.4 m) span deflected over 8.5-in (216 mm), as shown in Figure 5.
No delamination along the fiberglass-ICB interface was observed on any panel and debris was not found inside any of the culverts.

Figure 4. Dynamic Test Results

Figure 5. Dynamic Panel Deflection Measurements: 11-ft (3.4 m) span
MODEL DEVELOPMENT

PEC engineers were tasked with developing a material model and flexural resistance function for use in a fast running, SDOF analysis with corresponding response limits for design.

**Flexural Resistance Function.** The Mil-Tough® panel flexural model predicts the behavior of Mil-Tough® panels under dynamic loading. It takes user inputs on panel geometry and material properties and develops the full resistance function for the panel in flexure. For panels loaded with blast load only (no fragment load) the panel is assumed to have a high stiffness up to cracking and a reduced stiffness to ultimate rupture and failure of the panel as shown in Figure 6. In rebound, these panels exhibit a similar response except the panel is assumed to be cracked.

Some general material and mechanics assumptions were made in the development of the model. The list below provides a brief summary of these assumptions:

- plane sections remain plane (linear-strain profile)
- primary mode of behavior is flexural
- linear behavior between key points in the resistance function curve
- applied panel loading is uniform over the panel length

The load-deflection relationships were determined by relating the moment and curvature at key points in the Mil-Tough® panel flexural response to load and displacement, respectively. This conversion is performed based on beam mechanics and varies by support condition. The cracking moment was calculated when the tensile stress at the extreme fiber of the Mil-Tough® panel reached the modulus of rupture. The ultimate moment of the section was assumed to occur when the extreme tension fiber of the section reached the rupture strain of the fiberglass reinforcing. The resultants of the tension and compression forces in the section at this point were then used to calculate the nominal moment capacity of the section.

The model was calibrated to match the response of the static and dynamic flexural tests. In general, the new Mil-Tough® panels respond flexurally up to a large maximum deflection at midspan where a single hinge forms prior to failure by rupture of reinforcing. Calibration of the model was performed using the data from the last series of 6-ft (1.8 m) static beam bending tests as well as the load-tree tests. Figure 3 provides an example of the predicted resistance function overlaid on the experimental test data. The flexural model was also compared against the dynamic test data collected for the various panel types and spans in the arena blast test at AFRL. The model provided results which were generally conservative and typically predicted peak response quite well during dynamic testing. Figure 7 shows the resulting responses calculated using the Mil-Tough® panel flexural model resistance function with actual measured thicknesses and loads overlaid on the experimental blast test data. In general, predicted deflections using the actual charge weight and standoff or pressure-time history within 2-ft (0.61 m) and maximum actual panel thickness are within 10% of the measured deflections.
**Predictive Engineering Performance Tool.** The Mil-Tough® panel flexural model was designed specifically for use with the “Single-degree-of-freedom Blast Effects Design Spreadsheet” (SBEDS) version 4.1a dated 10 March 2009 developed by the U.S. Army Corps of Engineers (USACE) Protective Design Center (PDC). The model takes user inputs and generates a resistance function for use in dynamic SDOF...
calculations. The “User Inputs” sheet is the main user interface with the Mil-Tough® panel flexural model spreadsheet. The User Input sheet is divided into six sections: (1) Model Inputs, (2) SBEDS Inputs, (3) Resistance Function, (4) Shear Check, (5) SBEDS Response Criteria and (6) General Spreadsheet Information as illustrated in Figure 8 and summarized in Table 1. The parameters required to generate the resistance function in SBEDS are summarized in the “SBEDS Inputs” section of the User Inputs sheet. To perform a panel analysis, these values should be directly copied and pasted into the SBEDS General SDOF Program.

Figure 8. Mil-Tough® Panel Flexural Model Spreadsheet User Input Sheet

<table>
<thead>
<tr>
<th>No.</th>
<th>Section</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Model Inputs</td>
<td>User inputs for material properties, panel geometry, support condition and level of protection. All user inputs are highlighted in yellow.</td>
</tr>
<tr>
<td>2</td>
<td>SBEDS Inputs</td>
<td>Data for General SDOF Program in SBEDS</td>
</tr>
<tr>
<td>3</td>
<td>Resistance Function</td>
<td>Graphs the inward and rebound resistance function based on user inputs.</td>
</tr>
<tr>
<td>4</td>
<td>Shear Check</td>
<td>Calculates shear capacity and expected demand (at ultimate) based on user inputs.</td>
</tr>
<tr>
<td>5</td>
<td>SBEDS Response Criteria</td>
<td>Provides recommended design response limits based on user inputs for use in SBEDS General SDOF Program.</td>
</tr>
<tr>
<td>6</td>
<td>General Spreadsheet Info</td>
<td>Model version, date updated, and any pertinent logos.</td>
</tr>
</tbody>
</table>

Response Limits. The recommended design response limits are based on observations from both static and dynamic testing of Mil-Tough® blast and ballistic panels. Ultimate capacity was achieved in nearly all load-tree and 6-ft (1.8 m) span beam bending tests (except those where support bearing was lost due to large deformations). Therefore, the ultimate load and deflection relationships are well understood for the Mil-Tough® panels. The blast testing provided data on the behavior of panels under dynamic loading and illustrated that the Mil-Tough® panels
can achieve large deflections and high rotations while undergoing what is essentially elastic deformation in the fiberglass reinforcing.

Since the Mil-Tough® panels have a defined ultimate capacity at which rupture of reinforcing and complete fracture of the panels typically occurs (based on full-scale static load-tree tests); response limits have been recommended to limit behavior to the range prior to this point. Based on a review of materials exhibiting similar behavior and the levels of response achieved in static and dynamic testing, response limits have been provided to ensure that the panel response does not exceed this maximum value. Note that these response limits have been set conservatively due to the existing number of static and dynamic test data points available for this material.

Since the Mil-Tough® panel resistance curve does not have a defined yield point; “ductility” is a relative measure of the level of response with respect to ultimate. Therefore, a ductility of 1.0 would indicate that the panel achieved ultimate load and was essentially on the cusp of failure. Figure 9 shows the response limits as they apply to the resistance function that correspond to the allowable damage for non-structural components and levels of protection defined by the U.S. Army Corps of Engineers Protective Design Center Technical Report PDC TR 06-08.

![Figure 9. Response Limits for Mil-Tough® Panel Resistance Function](image)

**CONCLUSIONS**

The Mil-Tough® blast and ballistic panels, as tested, have the capacity to undergo large deflections and support rotations prior to failure. This behavior is achieved through uniform distribution of reinforcement in the cross-section, adequate bond between constituent materials (preventing the delamination failure mode), and consistency in material and geometric properties in production panels. The Mil-Tough® panel flexural model spreadsheet developed has the ability to predict the strength and deformation capacity of Mil-Tough® blast and ballistic panels both undamaged and pre-damaged (by small casing fragments or similar) panels accurately and consistently across a range of spans and panel thicknesses. The Mil-Tough® panel flexural model spreadsheet along with the recommended response limits associated with various levels of protection may be used in the design of Mil-Tough®
blast and ballistic panels within the applicable range of thicknesses and spans for commercial and protective applications.

REFERENCES
